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HEAT TRANSFER COEFFICIENT FOR CONDENSATION OF VAPORS OF WATER AND NON-MISCIBLE ORGANIC LIQUIDS ON HORIZONTAL TUBES

by

UTAH TSAO

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HEAT TRANSFER COEFFICIENT FOR CONDENSATION OF VAPORS OF WATER AND NON-MISCIBLE ORGANIC LIQUIDS ON HORIZONTAL TUBES *

By EDWIN M. BAKER † (Member) and UTAH TSAO ‡ (Non-Member)

Presented at the Buffalo-Niagara Falls, N. Y., Meeting, May 13-15, 1940

Abstract

Coefficients of heat transfer from vapor to a horizontal tube were determined for the condensation of mixed vapors of water and non-miscible organic liquids. This work is an extension of the research previously published by Baker and Mueller. In the present work a much wider range of vapor compositions was studied, for the systems water vapor mixed with vapors of benzene, toluene, chlorobenzene, trichlorethylene, and tetrachlorethylene.

The data were correlated into relatively the simple equations:

$$\frac{h_t}{1 - \frac{0.0167}{D}} = \frac{500}{1 - 0.0085 \text{ Vol. \% } H_2O} + 80$$

$$h_t = \frac{366 \sqrt[4]{\frac{1}{D}} \frac{(1 - 0.0284)}{D}}{1 - 0.0085 \text{ Vol. \% } H_2O} + \frac{1.67}{D}$$

The value of H given by either of these equations is independent of ΔT.

D = outside diameter of tube, ft.

h_t = coefficient of heat transfer, based upon ΔT, calculated from saturation temperature of the mixed vapor, B.t.u./(hr.) (°F.) (sq.ft.)

Introduction

The condensation of mixed vapors of non-miscible liquids on a horizontal tube may seem to be a narrow and unimportant problem. To consider the extent of the use of steam distillation in the organic and petroleum industries makes one immediately realize the importance of the problem.

The mechanism of the type of the condensation mentioned above is very complex. If two liquids wetted the condenser tube equally

* Submitted by Utah Tsao in partial fulfillment of the requirements for the Ph.D. Degree, University of Michigan.

† Professor of Chemical Engineering, University of Michigan.

‡ Department of Chemical Engineering, University of Michigan.

well, they would probably form films of liquids side by side on the tube. If neither of them wetted the tube, they would probably form drops of liquids side by side on the tube. If one liquid wetted the tube better than the other, the former would form a film on the tube, and the latter would form drops on the film. The last case is encountered when water and water-immiscible organic liquids are condensed on a copper tube.

Review of Previous Work

The condensation of mixed vapors is almost a virgin field. Very little previous work has been done. Kirkbride [5] established values of heat transfer coefficients for benzene and commercial petroleum products with water. Patterson, Weiland, Ruburgh, King and Huntington [8] worked on the heptane-water system in a vertical condenser. Baker and Mueller [1] worked on the non-miscible liquid systems benzene-water, toluene-water, heptane-water and trichloroethylene-water.

Present Apparatus

The condensation of the vapors of non-miscible liquids is usually drop-film type. The readings of thermocouples are erratic, and it was realized that thermocouples were not ideal for this type of work. A method which will give an average temperature of the whole tube was adopted. This method was recommended by J. O. Jeffrey.[3] The copper tube itself was used as a resistance thermometer. The total resistance of even a thin-walled copper tube is so low that special methods for measuring its resistance have to be used.

The apparatus is shown in Figure 1. The vapors of two non-miscible liquids, one of them water, generated from two separate stills, are mixed in a baffled container and finally are led to the main condenser under investigation. The main condenser (Figure 2) is provided with three windows for the observation of the conditions of condensation. Rubber stoppers are used as packing glands where the tubes pass through the ends of the jacket. Two circular canvas fins are attached to the condenser tube at points 44 inches apart. A trough under the tube is provided to collect the condensate formed between the fins. The excess vapor leaving the main condenser is completely condensed in a total condenser, on which a vent is provided to expel the non-condensible gases. Two Liebig glass condensers are attached

to the main condenser to collect and condense for analysis samples of inlet and outlet vapors. The pressure in the main condenser is measured by a mercury manometer.

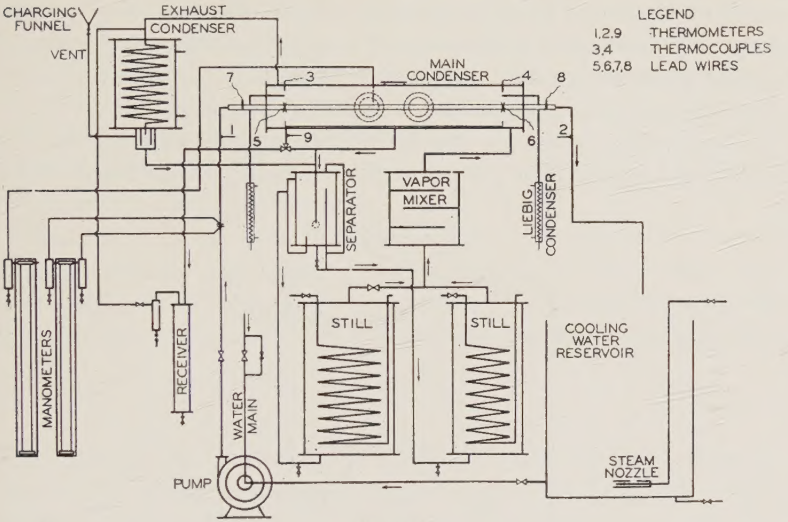

FIG. 1

All condensate is sent to an automatic separator which separates the non-miscible liquids and sends each back to the corresponding still. The condensate collected in the trough is sent to the separator under

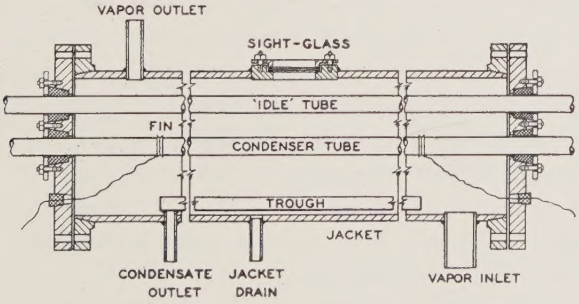

FIG. 2

ordinary conditions. It can also be sent to a small receiver for the determination of the rate of condensation by turning a three-way cock. A part of the pipe which carries away the condensate from the trough

is made of Pyrex glass tube so that the flow of the condensate can be observed at any time. Anything like plugging or choking in the pipe line can be detected immediately. The small condensate receiver is made from a 3-inch Pyrex glass cylinder. Any leakage of the three-way cock leading to the receiver can be quickly discovered. The vapor space of the receiver is vented to the main condenser. A spray of cooling water is provided on the outside wall of the receiver to cool the collected condensate before withdrawal for weighing.

The cooling water for the main condenser is recirculated by a centrifugal pump from a reservoir tank, which is provided with a

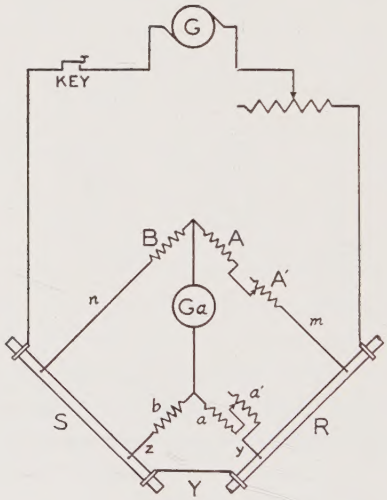

FIG. 3

steam heating device and an overflow connection. A city water line is connected to the suction side of the pump. A small by-pass line is attached across the valve regulating the city water in order to facilitate close adjustment of the temperature of the cooling water. The inlet and outlet water temperatures are measured by ordinary mercury thermometers. The velocity of cooling water is measured by a calibrated orifice with a mercury manometer.

For measuring the resistance of the condenser tube two copper wires are soldered around the condenser tube close to the fins. They are led to an electric circuit as shown in Figure 3. *G* is a direct current generator which delivers 150 amperes at 3 to 4 volts. *R* is the condenser tube. *S* is a shunt in a bath at constant temperature. The

temperature coefficient of the shunt is so low that its resistance remains practically constant within ordinary temperature variations of the bath. *Ga* is a sensitive galvanometer. *A, B, a,* and *b* are resistances of 1000 ohms. *A'* and *a'* are variable resistance boxes. One resistance box is chosen as a standard, and against this all the other resistance boxes are calibrated. In the bridge circuit only the ratio of the resistances are important; therefore no absolute standard resistance is required. Jeffrey set *A, B* and *a, b* at a definite ratio and adjusted *S* in order to balance the bridge. The present equipment is a slight modification. *S* is a fixed standard resistance, but *A'* and *a'* are adjusted to balance the bridge.

The total resistances of the lead wires, *m, n, y* and *z* are so small, compared with the 1000 ohms resistances *A, B, a,* and *b,* that they can be neglected. When the Kelvin bridge circuit is balanced the resistance of the tube can then be calculated by the following equation:

$$R = \frac{A + A'}{B} S \qquad (1)$$

Jeffrey showed that for a "thin-walled" tube with the value of $F = r_o/r_i = 1.25$ the temperature at any point in the tube wall is proportional to the radius at that point; and the relation between the mean temperature and resistance is as follows:

$$R = \frac{\beta_m L}{\pi r_i^2 (F^2 - 1)} \qquad (2)$$

Jeffrey also showed that for a thin-walled tube, with the variations of temperatures around and along the tube, the measured resistance of the tube gives a direct measure of its average resistivity and hence its temperature.*

After the average temperature is obtained the outside surface temperature of the tube can be calculated from ΔT across the tube. The ΔT across the tube can be calculated from the following equation:

$$\Delta T = T_o - T_i = \frac{\frac{Q}{\theta} ln \frac{r_o}{r_i}}{2\pi L k} \qquad (3)$$

Figure 4 is a plot of the temperature difference between the center of the tube (or average tube temperature) and the outside surface

* This method does not give the variation of temperature along the tube, which was shown by Mueller and Baker to be small if the cooling water was circulated at high velocity.

temperature of the tube, versus Q/θ (B.t.u. transferred per hour). This plot is more convenient than Equation (3), and also indicates the small magnitude of this correction for thin-walled tubes with small or moderate coefficients of heat transfer.

The heating effect of a current as large as 150 amperes is entirely negligible in the present experiments. The total resistance of the tube is around 400 micro ohms for the 20 gage 1-inch tube and 650 micro ohms for the 20 gage $\frac{5}{8}$-inch tube. The amount of heat produced by a current of 150 amperes is 8.4 B.t.u./hr. per ft. of the 1-inch tube, and 13.6 B.t.u. for the $\frac{5}{8}$-inch tube. Usually the rate of heat transfer in the present experiment is around 10,000 B.t.u./hr./ft. of tube and then the heating effect amounts to only about 0.1% even if the current

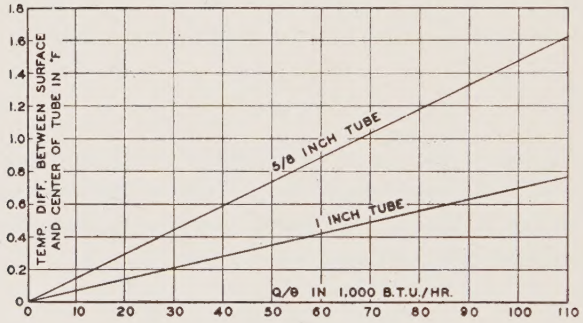

FIG. 4

is left on continuously. During the experiment only a few seconds are required to observe any swing of the beam of light on the scale of the galvanometer, and the current is flowing only when necessary for measurements of tube resistance.

The present equipment was set up without any inductance effect in the circuit to disturb the galvanometer when the circuit was intermittently connected. The current of 150 amperes goes through an "idle" condenser tube in the iron casing of the main condenser in one direction and returns in the test condenser tube in the opposite direction.

The copper tube, with its inner wall previously dried, was calibrated in place with benzene vapor and also with steam at different temperatures. It was found that the temperature coefficient of the

copper tube checks with the value given in the literature for copper; that is

$$R_t = R_o\ (1 + 0.0041151t - 0.0000019988t^2) \qquad (4)$$

where t = °C., R_t and R_o are the resistances at temperatures $t°$ and 0° C. respectively. The mean value of R_o calculated from different values of R_t does not deviate from the individual values of R_o more than 0.1%. For temperatures below 80° C. the relation between temperature and resistance was obtained by extrapolation of the above equation and checked by circulating water through the tube at different temperatures where there was no vapor in the condenser. The temperature of the water was measured by a mercury thermometer previously calibrated against a standard thermometer.

The resistance of the tube was checked frequently, and was found to vary little or not at all from day to day, unless some vapor which attacks copper was introduced; nevertheless the calibration was checked frequently.

The sensitiveness of the equipment is about 0.1° F.

Procedure

Before starting to make a run, all cooling water was turned on first and then steam to the stills. For several hours the apparatus thus was heated up thoroughly. The cooling water was maintained at a temperature and flow rate as constant as possible. The temperature of the cooling water controlled the temperature drop for each run.

During a run readings were taken of the thermocouples in the vapor phase, the inlet and the outlet temperatures of the cooling water, the temperature of the condensate, the Kelvin bridge readings, the rate of flow of cooling water, and the pressure in the main condenser. When these readings remained constant for five minutes a sample of condensate was collected within a short interval of 30 seconds to two minutes, depending upon the rate of flow of the condensate. All readings were checked in the beginning, in the middle and at the end of collection of a sample. The condensate was cooled and weighed. For the non-miscible liquid systems the analysis was carried out simply by separating the two components in a separatory funnel and weighing the separated parts. The condensates collected from the

auxiliary condenser during the run were also analyzed for their compositions. After analysis all the condensates were returned to the apparatus through a funnel connected to the automatic separator.

From the amount and composition of the condensate the heat transferred through the section of the tube between fins can be calculated.

There are two orifices on the two steam lines leading to the two vapor generators. The relative amount of heat supplied to each generator can be maintained constant by keeping same reading on the manometers in the steam lines; thus the composition of the vapor to the main condenser is kept constant. The vapor temperature is a good indicator of the vapor composition. The thermocouples in the vapor phase indicate almost instantaneously any change of vapor composition.

Physical Properties of Binary Systems of Non-Miscible Liquids

When the pressure and the composition of the vapor of a binary system of non-miscible liquids are fixed the temperature for equilibrium is definite. The temperature at which *only* one vapor is saturated, *i.e.*, is in equilibrium with its liquid, is defined as the "dew point temperature" of the vapor mixture. The dew point temperature at fixed pressure will vary with vapor composition, and the lowest dew point temperature, sometimes called the pseudo-azeotropic temperature, is defined as the "eutectic temperature." At the eutectic temperature the relative concentrations of the two components in the vapor are proportional to their vapor pressures at that temperature. This vapor mixture is defined as the eutectic mixture. Thermodynamically the eutectic mixture is the most stable mixture, because if any partial condensation of the mixture occurs the non-eutectic mixtures always tend to change into the eutectic mixture.

The vapor mixtures led to the main condenser were in the dew point state or eutectic state under all experimental conditions. For low temperature drops in the condenser the vapors of non-eutectic mixtures change composition during condensation, due to the partial condensation of the excess component in the mixture. The eutectic mixture will condense at even very low temperature drops without any change of the vapor composition.

Calculation of the Heat Transfer Coefficient for the Condensing Film

The organic liquids under investigation all have better adhesion tension with copper than does water. Therefore the organic film wraps the entire tube, and water drops float on or rather are immersed in the organic film. The vapor next to the condensing film must be of eutectic composition, because at this point there exists a three-phase condition of two non-miscible components. Therefore the true temperature gradient across the vapor film is the difference between the temperature of the surface of the tube and the eutectic vapor temperature of the mixture under the existing pressure. For all the calculations of the vapor film heat transfer coefficient h from the experimental data this temperature difference is used for the temperature drop ΔT in the equation

$$h_t = \frac{Q/\theta}{\Delta T \times A} \tag{5}$$

To calculate the heat transferred through the tube between the fins from the amount of the condensate collected in the trough during a certain time interval is rather simple. Since the two liquids are non-miscible they can be treated separately as two individual liquids. The total amount of heat transferred can therefore be calculated as the summation of the weight of each component multiplied by the latent heat of vaporization of each component at the eutectic temperature, plus the heat of cooling the vapor from the dew point temperature to the eutectic temperature. The latter usually amounts only to a fraction of one per cent of the former.

The total outside area of the condenser tube between the fins is 0.96 sq. ft. for the 1-inch tube, and 0.60 sq. ft. for the $\frac{5}{8}$-inch tube. The time intervals in the experiment were measured by an electric clock with a long second hand.

Correlation of Data and Explanation of the Results

Nusselt's equation for condensing pure vapors is as follows: *

$$h = 0.725 \left(\frac{k^3 \rho^2 g}{D\mu(\Delta T)} \right)^{1/4} \tag{6}$$

* See nomenclature, page 538.

Kirkbride presented an equation for the condensation of binary systems of non-miscible liquids as follows:

$$h = \frac{h_w Q_w + h_s Q_s}{Q_w + Q_s} \qquad (7)$$

where the individual film coefficients were determined by the Nusselt equation. Baker and Mueller pointed out that the above equation is unsound mathematically.

Baker and Mueller presented an empirical equation for several mixtures:

$$h \left(\frac{\mu^2}{k_m \rho_m^2 g} \right)^{1/3} = 1.28 \left(\frac{C_{pm} \mu \rho a \tau'^{0.7}}{k_m \lambda_m} \right)^{2.38} \left(\frac{Q_s}{Q} \right)^{-3.28} \qquad (8)$$

where ρ, C_p, λ of the mixtures were determined according to the weight of each component present and k was weighted on the basis of the volume of each component in the liquid phase. The viscosity, μ, was not weighted, but the viscosity of the component forming the film in the drop-film type condensation was used.

Baker and Mueller tested a narrow range of Q_s/Q and warned against using their equation for a wider range than covered experimentally. This research shows that the warning was justified.

This research confirmed the finding of Baker and Mueller that the temperature drop ΔT has little or no effect upon the heat transfer coefficient h, and further showed that the coefficient decreases with a *decrease* in the diameter of the tube.

Both of these findings show that the Nusselt equation for the condensation of a single vapor on a horizontal tube will not apply to the condensation of mixed vapors of non-miscible liquids. This is perhaps surprising, as the tube is covered with a film of organic liquid, which preferentially wets the tube.

Unfortunately, values of the group $\left(\frac{k^3 \rho^2 \lambda}{\mu} \right)^{1/4}$ for all of the organic liquids tested do not differ by more than 10% of the mean value. Hence, even if some modification to the Nusselt equation could be applied to the resistance of heat transfer of the organic liquid film, the different systems of liquids tested would not reveal with certainty any effect of the change in value of this group of physical properties.

Mechanism of Condensation.—It is observed in the experiment that the water forms drops which are immersed in the organic film. These water drops roughen the surface of the film of the organic liquid and imbed the film with a material of relatively high thermal conductivity. This will improve the thermal conductivity of the organic film, which is the controlling film. The higher the percentage of water in the condensate the rougher the organic film. Hence an empirical factor such as $\frac{1}{1 - C \times \text{Vol. \% } H_2O}$ might well be expected to apply to an equation for the film coefficient for drop-film condensation. This group really represents the roughness of the organic film. For each tube diameter, plots were made of h_t versus $\frac{1}{1 - 0.0085 \times \text{Vol. \% } H_2O}$. These are shown in Figures (7) and (8). The correlation, while not perfect, is relatively good and at this stage of our knowledge may be considered satisfactory.

The actual mechanism of condensation was studied for some indication of the effect of tube diameter on heat transfer coefficient. According to the Nusselt equation for the condensation of single vapors on horizontal tubes, smaller tubes should have higher heat transfer coefficients than the larger tubes, but the present experimental results on the vapors of non-miscible liquid mixtures indicated the opposite effect. The explanation of this lies in the roughening effect of the organic film next to the tube by imbedded water drops. Also during the condensation of vapors of non-miscible liquids large drops of organic liquid hang on the bottom of the tube before they grow large enough to drip off the tube.

The organic film on the bottom of the tube is therefore very thick. The water drops which form on the organic film may leave the film by the combination of centrifugal and gravitational forces before they reach the very bottom of the tube. For these two reasons there is not much roughening effect of water drops on the film on the bottom portion of the tube. This part may be considered inert to the roughening effect. The extent of this "inert" part of the tube surface depends upon the physical properties of the liquid covering that part and is about the same for large and small tubes. The *proportion* of the surface which is inert is naturally greater for small tubes than for larger tubes. The heat transfer coefficient for large and small tubes therefore should be capable of correlation by multiplying each with

a proportionality factor. The empirical factor found was $\frac{1}{1-\frac{0.0167}{D}}$. Using this factor results for 5/8, 1, and 1.313 inch tubes can be correlated very well.

A plot of $\frac{h_t}{1-\frac{0.0167}{D}}$ versus $\frac{1}{1-0.0085 \times \text{Vol. \% } H_2O}$ was made for all the data obtained when the tube temperatures were below the dew point of both components at their partial pressures in the vapor

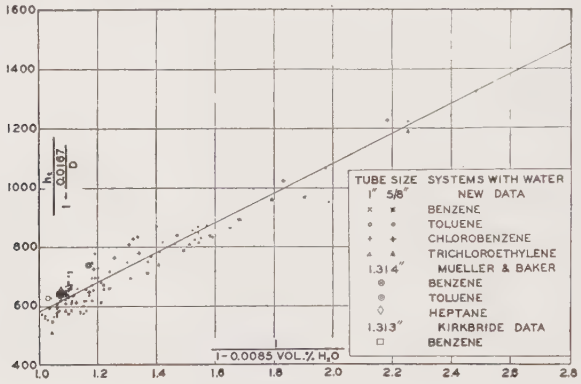

FIG. 5

mixtures. This plot is shown in Figure (5), and from it an equation was derived, as follows:

$$\frac{h_t}{1-\frac{0.0167}{D}} = \frac{500}{1-0.0085 \text{ Vol. \% } H_2O} + 80 \qquad (9)$$

From this equation the values of h_t were calculated and compared with the values of h_t observed in the experiments. The maximum deviation for different vapor mixtures does not exceed 15% except for the tetrachlorethylene-water system, and for a few runs where the tube temperatures were below the dew point of only one component.

The tetrachlorethylene-water mixture attacked the copper condensing tube used, and the experimental data were rather erratic. Therefore no data were plotted on the tetrachlorethylene-water system. The observed values of h_t for this system were generally high, and

rather indifferent to the composition of vapor mixtures. The changing surface condition of tube resulting from chemical reaction caused water drops to attach directly to the tube and to be held on the tube rather firmly. These water drops roughen the tetrachlorethylene film from inside. The extent of this kind of roughening depends entirely upon the size and number of water drops, which are determined much more by the nature of tube surface than by the proportion of water in the condensate.

Tube Temperature Above Dew Point of One Component.—When the temperature of the condensing tube is above the dew point of only one component of the vapor mixture partial condensation oc-

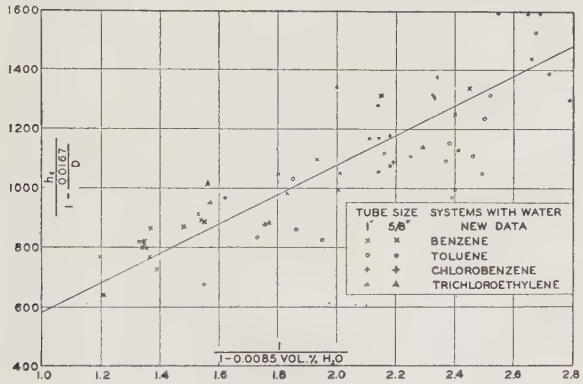

FIG. 6

curred on the tube. The data do not correlate well on any basis, but a fair correlation was obtained by using the average composition of inlet and outlet vapor in place of composition of the condensate collected from the condensing tube. The results of this correlation are plotted in Figure 6, but the corresponding data are not given in the tables.

Alternate Correlation.—Equation (9) is subject to the criticism that for a tube diameter of 0.0167 ft. the calculated value of h_t is 0, and for smaller diameters h_t is negative. It is a simple relationship which showed satisfactory results for tube diameter of about ½ inch to 1½ inch.

An equation free from these objections can be developed by assuming a constant width at the bottom of the tube blanketed by thick drops of organic liquid, and computing the mean coefficient h as a weighted average of the coefficient on this blanketed portion of

the tube and the coefficient on the part of the tube roughened by the water drops. Thus

$$h_t = \frac{h_a(\pi D - B) + h_b B}{\pi D} \qquad (10)$$

where, h_t = coefficient of heat transfer for entire tube
h_a = coefficient of heat transfer for portion of tube roughened by water drops
h_b = coefficient of heat transfer for blanketed portion of tube
B = width of tube blanketed, ft.
D = diameter of tube, ft.

The value of h_a should be affected both by the roughening effect of the water drops, and should also respond to the amount of condensate formed on the tube. Therefore h_a, according to the Nusselt concept, should be proportional to $\left(\frac{1}{D}\right)^{1/4}$.

Therefore

$$h_t = \frac{C\sqrt[4]{\frac{1}{D}}\left(1 - \frac{B}{\pi D}\right)}{1 - 0.0085 \text{ Vol. \% } H_2O} + \frac{h_b B}{\pi D} \qquad (9)$$

where C is a constant.

Evaluation of the constants, from the data of this research, gives

$$h_t = \frac{366\sqrt[4]{\frac{1}{D}}\left(1 - \frac{0.0284}{D}\right)}{1 - 0.0085 \text{ Vol. \% } H_2O} + \frac{1.67}{D} \qquad (10)$$

and, for a 5/8 inch O.D. tube

$$h_t = \frac{350}{1 - 0.0085 \text{ Vol. \% } H_2O} + 32 \qquad (11)$$

for a 1 inch O.D. tube

$$h_t = \frac{450}{1 - 0.0085 \text{ Vol. \% } H_2O} + 20 \qquad (12)$$

for a 1.314 inch O.D. tube

$$h_t = \frac{471}{1 - 0.0085 \text{ Vol. \% } H_2O} + 15.2 \qquad (13)$$

All of the data for these three tube diameters are plotted in Figures 7 and 8. A few of the data and results of calculation are tabulated in Table I.*

* Complete data are given in the dissertation, filed with the Horace H. Rackham School of Graduate Studies, Ann Arbor, Mich.

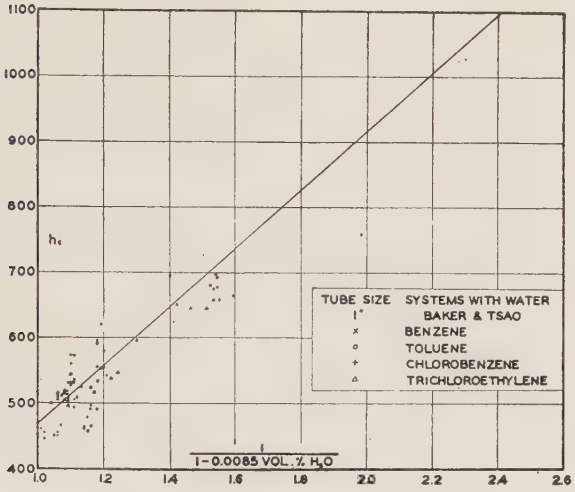
1100
1000
900
800
700
600
500
400
h_t
TUBE SIZE SYSTEMS WITH WATER
1" BAKER & TSAO
× BENZENE
○ TOLUENE
+ CHLOROBENZENE
△ TRICHLOROETHYLENE
1 − 0.0085 VOL. % H_2O
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6

FIG. 7

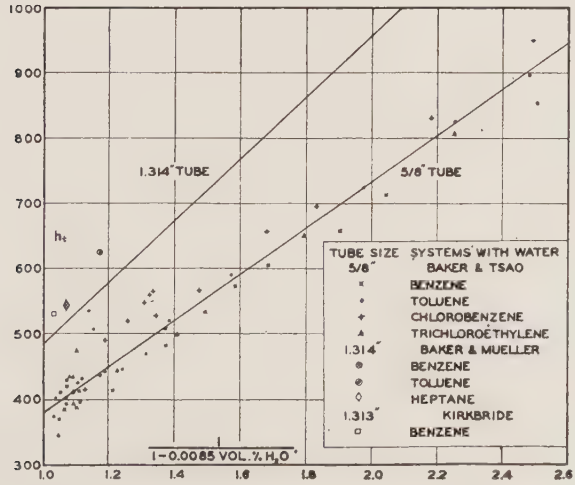
1000
900
800
700
600
500
400
300
h_t
1.314" TUBE
5/8" TUBE
TUBE SIZE SYSTEMS WITH WATER
5/8" BAKER & TSAO
× BENZENE
• TOLUENE
+ CHLOROBENZENE
▲ TRICHLOROETHYLENE
1.314" BAKER & MUELLER
⊕ BENZENE
⊕ TOLUENE
◊ HEPTANE
1.313" KIRKBRIDE
□ BENZENE
1 − 0.0085 VOL. % H_2O
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6

FIG. 8

TABLE I.—PARTIAL TABULATION

Run	Pressure m.m. Hg.	Mean Tube	Saturation	Mean ΔT	Temperature in °F. Vapor In	Vapor Out	Condensate	Cooling Wa In	C
				Benzene-water 1 inch tube					
11	746.5	109.4	155.9	46.5	162.5	157.8	....	76.5	8
18	747.3	139.5	156.0	17.5	163.3	159.3	....	131.5	13
34	741.9	106.8	155.6	48.8	184.3	178.3	152.0	59.0	6
49	741.7	123.2	155.6	32.4	193.6	190.6	152.0	85.1	8
51	741.7	114.8	155.6	40.8	197.1	193.5	153.0	59.0	6
127	745.0	107.1	155.8	48.7	170.3	169.3	149.0	56.8	6
128	749.0	106.4	156.1	49.7	167.7	166.7	156.0	57.2	6
132	750.0	116.5	156.1	39.6	156.4	156.4	154.0	77.0	8
				Toluene-water 1 inch tube					
63	740.9	133.8	183.0	49.2	202.8	201.0	178.0	77.0	8
71	744.5	138.2	183.3	45.1	183.7	183.7	177.5	104.0	10
73	744.7	157.7	183.3	25.6	183.9	183.9	178.0	140.0	14
79	742.4	128.5	183.2	55.7	200.7	199.3	178.0	59.9	6
95	743.3	126.1	183.2	57.1	187.4	186.4	176.5	68.0	7
				Chlorobenzene-water 1 inch tube					
111	744.9	138.5	194.8	56.3	200.9	200.5	189.0	68.0	7
115	741.5	142.5	194.5	52.0	205.3	204.7	190.0	68.0	7
121	749.4	135.1	195.0	59.9	197.7	196.9	190.0	62.6	6
122	749.2	138.2	195.0	56.8	199.0	195.6	189.0	77.0	8
124	741.0	129.7	194.5	64.8	219.7	205.1	188.0	60.8	6
126	752.9	127.1	195.2	68.1	230.4	220.4	193.0	60.8	6
				Trichlorethylene-water 1 inch tube					
142	742.0	112.2	162.0	49.8	172.2	170.8	160.0	57.2	6
145	742.0	112.2	162.0	49.8	168.3	166.9	159.0	57.4	6
148	742.0	111.5	162.0	50.5	164.9	163.7	159.0	57.4	6
174	743.5	113.5	162.0	48.5	183.1	178.7	159.0	55.4	5
177	744.5	117.9	162.1	44.2	196.7	193.3	161.0	55.4	5
189	765.4	125.6	163.5	37.9	166.4	165.8	159.0	86.0	8
				Benzene-water ⅝ inch tube					
193	743.0	64.1	155.6	91.5	158.4	157.6	151.0	47.7	5
198	748.4	101.4	156.0	54.6	157.2	156.8	153.5	95.0	9
199	748.4	124.2	156.0	31.8	156.8	156.4	154.0	122.0	12
203	749.0	109.8	156.1	46.3	166.4	164.0	152.0	104.0	10
205	745.0	96.6	155.8	59.2	183.3	179.3	152.0	86.0	9
207	744.0	69.4	155.7	86.3	192.3	189.1	152.0	47.7	5

IMENTAL AND CALCULATED DATA

Wt. of Condensate lbs./hr.	Q/θ	Composition in Wt. % H_2O Vapor In	Vapor Out	Condensate	h_t Cal.	h_t Obs.	$\frac{1}{1-0.0085 \text{ Vol. \% } H_2O}$
			Benzene-water 1 inch tube				
86.7	23,100	13.0	14.7	10.76	509	517	1.09
30.4	8,500	11.2	11.2	12.43	518	505	1.11
69.1	25,400	...	...	22.20	563	542	1.21
39.4	19,410	37.4	30.0	36.8	655	624	1.41
52.8	28,450	41.4	34.0	42.1	695	726	1.50
117.5	21,500	...	...	0.56	472	460	1.01
110.5	21,650	...	...	2.25	475	454	1.02
75.5	17,300	...	...	6.60	495	455	1.06
			Toluene-water 1 inch tube				
55.1	32,500	50.0	44.6	50.8	760	688	1.65
78.6	21,360	24.6	20.7	18.76	540	492	1.16
35.9	12,100	20.3	22.1	21.10	548	492	1.18
65.0	35,200	43.6	38.3	45.1	705	658	1.53
87.0	30,400	24.1	22.2	22.3	540	555	1.19
			Chlorobenzene-water 1 inch tube				
75.8	36,600	39.1	37.8	39.9	710	677	1.54
60.6	37,850	56.5	49.0	56.8	907	759	1.98
88.9	37,400	33.7	30.6	33.0	656	650	1.42
90.5	32,500	27.8	...	25.5	601	596	1.30
117.2	34,400	...	...	16.7	550	554	1.18
128.5	33,400	...	...	11.8	522	510	1.12
			Trichlorethylene-water 1 inch tube				
178.4	23,850	...	...	3.11	487	500	1.04
161.0	24,500	...	...	5.28	500	513	1.07
148.7	24,000	...	...	6.41	510	495	1.09
100.1	25,050	...	...	15.50	566	537	1.22
68.9	27,400	29.1	25.1	31.4	697	645	1.51
99.9	19,200	7.5	7.2	9.68	527	527	1.13
			Benzene-water ⅝ inch tube				
102.0	22,050	8.2	8.0	4.07	392	402	1.035
53.3	12,900	8.1	8.3	8.20	403	394	1.066
33.5	8,200	8.8	8.5	8.50	405	430	1.070
40.9	11,500	12.1	10.5	12.63	418	414	1.107
40.8	15,900	22.0	18.7	24.9	463	447	1.24
52.7	25,000	32,9	27,0	34,5	510	483	1,37

TABL

Run	Pressure m.m. Hg.	Mean Tube	Saturation	Mean ΔT	Temperature in °F. Vapor In	Vapor Out	Condensate	Cooling Wa In	
				Benzene-water ⅝ inch tube					
208	744.0	98.1	155.7	57.6	194.2	188.8	153.0	86.0	
209	743.0	71.6	155.7	84.1	198.3	195.1	153.0	46.9	
211	743.0	72.7	155.7	83.0	200.0	196.8	152.5	46.8	
212	743.0	74.6	155.7	81.1	202.7	199.1	153.5	46.8	
213	741.0	76.6	155.5	78.9	203.8	200.8	153.0	46.8	
				Toluene-water ⅝ inch tube					
219	755.2	128.1	183.9	55.8	208.5	207.1	188.0	122.0	12
221	753.0	70.2	183.8	113.6	191.4	188.6	176.0	46.4	
224	753.8	70.6	183.8	113.2	183.4	183.6	176.0	45.9	
225	751.8	74.8	183.7	108.9	194.0	192.4	177.0	45.9	
227	745.8	78.6	183.4	104.8	200.0	198.2	178.0	46.4	
228	747.8	87.3	183.5	96.2	205.9	204.1	179.0	46.4	
229	746.8	89.2	183.5	94.3	207.1	205.3	179.0	46.4	
230	744.8	82.8	183.3	100.5	204.0	202.6	179.0	45.9	
				Trichlorethylene-water ⅝ inch tube					
238	748.0	65.6	162.4	96.8	171.4	172.2	159.5	45.9	
240	748.5	127.9	162.4	34.5	163.9	163.5	160.5	122.0	12
243	753.0	69.2	162.7	93.5	182.9	179.7	159.5	45.9	
244	747.5	76.6	162.4	85.8	200.7	198.7	160.0	45.9	
245	749.5	69.5	162.5	93.0	193.3	190.1	159.0	45.9	
246	748.5	80.8	162.4	81.6	203.9	202.3	161.0	45.9	
				Chlorobenzene-water ⅝ inch tube					
249	749.5	73.4	195.0	121.6	222.1	214.7	191.0	45.9	
252	750.0	135.6	195.0	59.4	196.1	193.9	190.0	122.0	12
253	745.0	130.8	194.7	63.9	229.8	220.2	195.0	122.0	12
254	743.6	130.9	194.6	63.7	213.3	207.3	192.0	122.0	12
256	741.5	170.7	195.0	24.3	194.0	193.5	190.0	167.0	16
258	743.0	83.6	194.6	111.0	197.8	197.0	188.0	46.9	
259	742.5	88.8	194.5	105.7	203.2	202.0	188.0	47.1	
260	744.5	94.5	194.7	100.2	205.4	204.4	190.0	47.1	
261	742.5	98.8	194.5	95.7	206.6	205.6	190.0	47.1	
265	742.0	138.4	194.5	56.1	202.0	200.6	190.0	122.0	12

nued

Wt. of Condensate lbs./hr.	Q/θ	Composition in Wt. % H_2O Vapor In	Vapor Out	Condensate	h_t Cal.	h_t Obs.	$\frac{1}{1-0.0085 \text{ Vol. \% } H_2O}$
			Benzene-water ⅝ inch tube				
34.7	18,460	34.7	29.4	41.5	550	534	1.49
50.4	28,900	43.6	36.6	46.2	584	573	1.58
49.2	30,120	47.3	40.4	50.7	620	605	1.68
47.1	32,000	54.0	45.1	58.7	700	657	1.90
46.9	33,700	58.6	49.1	63.2	747	712	2.04
			Toluene-water ⅝ inch tube				
66.5	12,550	6.7	7.6	3.81	390	375	1.030
105.0	29,400	13.5	15.1	14.55	420	431	1.117
88.1	30,050	20.7	19.7	21.60	444	443	1.185
72.0	33,250	37.1	30.6	35.9	510	509	1.37
66.6	37,100	47.4	40.6	47.0	581	590	1.57
64.6	47,900	68.9	57.1	69.2	822	829	2.25
64.8	50,700	73.6	61.0	74.0	905	897	2.48
63.5	43,600	63.5	53.0	62.5	724	724	1.97
			Trichlorethylene-water ⅝ inch tube				
145.7	20,000	3.8	4.5	3.31	394	344	1.045
54.4	8,980	6.7	6.7	6.67	410	434	1.087
99.1	24,900	15.1	12.6	15.67	458	444	1.223
66.5	33,500	41.1	34.6	43.00	660	650	1.790
79.0	27,800	25.4	22.0	26.35	522	499	1.405
62.5	39,400	51.3	43.6	56.70	822	805	2.250
			Chlorobenzene-water ⅝ inch tube				
118.0	30,300	...	15.8	12.63	423	415	1.125
53.3	19,500	27.6	28.1	26.50	487	548	1.305
68.7	15,800	11.1	14.2	9.31	411	412	1.090
59.5	16,750	17.2	19.2	16.00	440	438	1.170
20.1	7,700	29.2	28.4	28.60	500	528	1.340
84.5	37,800	35.0	34.1	36.2	545	567	1.470
75.7	44,000	51.0	46.8	51.8	674	694	1.830
74.9	50,000	60.4	55.3	62.2	797	831	2.180
74.9	54,600	67.3	60.7	69.3	908	951	2.490
41.7	22,150	42.9	41.2	46.0	620	658	1.680

Heat transfer coefficients for the condensation of single vapors were also determined. Since all the organic liquids used are all of technical grade, vapor temperatures instead of theoretical saturation temperatures were used for the calculation of these temperature drops across the film. The values of "h observed" were compared with the values calculated from Nusselt's equation. They were found to check within 10% except for runs of low temperature drop, and may be published later.

The quantity of heat transferred Q/θ tabulated in Table I is only about 44/54 of the quantity of heat transferred calculated from the rate of flow and the inlet and outlet temperatures of the cooling water, because the quantities tabulated were calculated from condensate collected between the fins 44 inches apart while the total length of condenser tube exposed to the vapor is 54 inches.

Sources of Data. All of the latent heats of vaporization and the densities used in the calculation are evaluated at the saturation temperature of the mixture.

The latent heat of water was obtained from Keenan's Steam Tables [4]; that of benzene, from McAdams "Heat Transmission" [6]; that of toluene from Wiss. Veroffentlich Siemans-Konzern [7]; and that of trichlorethylene from Refrigerating Engineering.[2] The latent heat of tetrachlorethylene was obtained from the International Critical Tables,[12] and the temperature coefficient of latent heat was assumed as −0.065 B.t.u./°F., which is the experimental value for trichlorethylene. The latent heat of chlorobenzene was obtained from Industrial and Engineering Chemistry.[9] The densities, viscosities, and vapor pressures at different temperatures of all the materials used were obtained from the International Critical Tables. The thermal conductivities of benzene and tetrachlorethylene were obtained from the International Critical Tables. Those of chlorobenzene and toluene were obtained from Transactions of the American Society of Mechanical Engineers.[11] The thermal conductivity of trichlorethylene was calculated by an equation given in the above article. The value found was 0.0737 at 30° C. Baker and Mueller used a value of 0.127 which was calculated from an older equation of the same author. From the characteristics of the empirical equation for the calculation of thermal conductivities the values for trichlorethylene and tetrachlorethylene were expected to be close together. The new value calculated is more reasonable, because it is closer to the experimental value 0.0728 of

tetrachlorethylene. The temperature coefficient of thermal conductivities for both trichlorethylene and tetrachlorethylene were assumed as −0.00005 per degree F. Eutectic temperatures were calculated from gas laws and vapor pressures, assuming no mutual solubility of the liquids.

Summary of Conclusions

The present work satisfactorily overcame the difficulties of measuring the mean surface temperature of the condenser tube.

At the eutectic temperature both of the two non-miscible liquids will coexist with their vapors under equilibrium conditions. The eutectic temperature was used to calculate the temperature drops across the condensing film. Satisfactory correlations were obtained on this basis, but not on the basis of the actual vapor temperature less the temperature of the tube surface.

Kirkbride studied too narrow a range of composition of vapor mixture to derive a general equation for the condensation of mixed vapors of non-miscible liquids with justification. Baker and Mueller investigated four vapor mixtures with the composition range limited to eutectic mixtures of each vapor mixture, and to mixtures not differing greatly from eutectic mixtures, and their empirical equation may not be applied to an extended range of composition.

In the present work an approach based upon an analysis of the mechanism of condensation was tried. A mechanical mechanism of the condensation of the vapors of non-miscible liquids was discovered. This mechanism overshadowed many of the conventional physical properties of the condensing liquids which influence heat transfer coefficients. From a study of this mechanism, a simple empirical equation was derived. This equation correlates not only the data of four vapor mixtures with extensive variation of vapor compositions and temperature drops for the two tube sizes of the present work, but also the data of Kirkbride and the data of Baker and Muller for another tube size and another additional vapor mixture.

For further investigation of condensation along the same line different condensing surfaces may be tried. If a condensing surface should be found which is preferentially wetted by water and not by the organic liquid, quite different coefficients may be expected.

Nomenclature

A = area, sq. ft.
B = width of tube blanketed with thick organic drops, ft.
D = outside diameter of tube, ft.
$F = r_o/r_i$
L = length of tube, ft.
Q/θ = heat transferred, B.t.u./hr.
T = tube-wall temperature, °F.
ΔT = temperature drop, °F.
c_p = specific heat, B.t.u./(lb.)(°F.)
g = acceleration of gravity, 4.18×10^8 ft./(hr.)(hr.)
h = coefficient of heat transfer, B.t.u./(hr.)(°F.)(sq.ft.)
h_a = coefficient of heat transfer for portion of tube roughened by water drops.
h_b = coefficient of heat transfer for blanketed portion of tube
h_t = coefficient of heat transfer, based upon ΔT calculated from saturation temperature of the mixed vapor, B.t.u./(hr.)(°F.)(sq.ft.)
k = thermal conductivity of condensate film, B.t.u./(hr.)(sq. ft.)(°F./ft.)
r = radius of tube, inch.
α = temperature coefficient of resistance, ohm/°F.
β_m = resistivity at mean temperature T_m, ohm/(ft.)(sq.ft.)
μ = viscosity, lbs./(ft.)(hr.)
λ = latent heat of vaporization, B.t.u./lb.
ρ = density of condensate, lb./cu.ft.

Subscripts

i = inside
m = mean value
o = outside
s = second component
w = water

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Discussion

A. P. Colburn (University of Delaware, Newark, Del.): Did you make a heat balance on the heat removed from the condensate compared with that picked up by the cooling water?

The reason for asking that is this: The vapor temperature, as you point out, for all except pseudo-azeotropic condensation is higher than the condensing temperature. The material that collects in the trough, therefore, is at a different temperature than the vapors. We would expect that what you eventually draw out of the exchangers contains less liquid than is actually condensed on the tube.

E. M. Baker: We did make some heat balances, and these checked within the order of about 10 per cent, when allowance was made for the fraction of the tube or heating surface from which condensate was collected. Precise checks would not be expected for at least two reasons. Water was circulated through the tube at high velocity, and the quantity of water was measured only by an orifice meter. The temperature rise of the water was small, and the inlet and outlet water temperatures were measured by ordinary mercury thermometers without mixing chambers.

The condensate falling into the trough would be somewhat "supercooled," and there was no visible boiling of the condensate in the trough. We felt that the heat balances made did indicate that the heat quantities calculated from the condensate were dependable.

Further discussion of this paper may be published in Volume 36, No. 6, December 25, 1940.